Higgs Short Notes

Higgs Field, Vacuum Nightmares, End of the World

Production, Decays

Strategies, Detectors

Observation

About the Higgs Field - I

Universal, constant field

Lorentz scalar $\rightarrow$ Same value in any frame, rotation invariant

Non-standard feature:

Vacuum expectation value $v \neq 0$

Usual analogy: Spontaneously magnetized ferromagnet:

$\mathbf{M} \neq 0$ below Curie temperature

$\rightarrow$ Pick up a direction

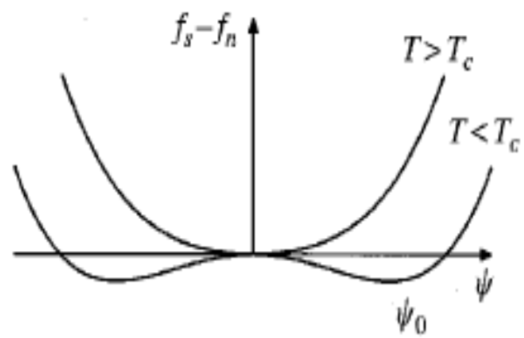
Ground state rotationally not symmetric, in spite of H being symmetric

About the Higgs Field - II

Better analogy: Superconductor
Energy difference between normal and s.c. state at two different temperatures

$$\Delta E = a(T)|\psi|^2 + \frac{1}{2}b(T)|\psi|^4 + \ldots$$ Landau theory of phase transitions

ψ is the Cooper pair 'wave function' → $|\psi|^2$ ~ density of Cooper pairs



Below T_c, the minimum energy state ('vacuum') occurs for $\psi = \psi_0 \neq 0$, phase undefined
→*U(1) QED* gauge invariance spontaneously broken

→ Photon becomes 'massive' → $\boldsymbol{B} = 0$ inside

About the Higgs Field - III

ψ 'Higgs field' of superconductivity: $<\psi>\neq 0$ $\leftrightarrow$ Permanent supercurrents

Superconductive state:
'Higgs field' = 'Wave function' of Cooper pairs

→Not a fundamental field
→'Composite' field of fundamentals fermions (electrons)

Why there is the composite?

e-*e* effective interaction: Attractive (!) due to *e* – lattice interaction

Is the 'real' Higgs field a genuine, fundamental field or a composite?

Good question..No answer (yet):
Take it as a fundamental field

About the Higgs Field - IV

A couple of questions:

1) What about the nonzero VEV of the Higgs field?

Higgs: Unique field whose VEV $\neq 0$

Similar to magnetization $\mathbf{M} \neq 0$ in a ferromagnet

But:

In a vacuum $\rightarrow$ Not related to many body effects

Lorentz scalar $\rightarrow$ No preferred direction, reference frame

2) Does it involve a new force? 'Giving mass to $\approx$all the fundamental constituents' ??

• Part of the standard EW interaction, often as a negligible contribution:

Higgs *particle* exchange diagrams between Fermion lines normally strongly suppressed

by m_f / m_W factors as compared to $\gamma, Z^0, W^{\pm}$ exchange (Not true for t quark!)

$3-$ & $4-$boson diagrams with and without H similar

• Crucial role as 'Background' interaction:

For most particles Higgs *field* coupling translates into *inertial mass* !

About the Higgs Field - V

Apparently contributing to vacuum energy density:

Beware: Take *potential energy* $V(\phi)$

$$
\begin{aligned}
V_{\min} = V(v) &= \frac{1}{2}\mu^2 v^2 + \frac{1}{4}\lambda v^4 \quad \text{use } \mu^2 = -\lambda v^2 \\
&= -\frac{1}{4}\lambda v^4 \qquad \text{use } m_h^2 = 2\lambda v^2 \\
&= -\frac{1}{8} m_h^2 v^2
\end{aligned}
$$

Constant term: Usually not considered

Does not enter field equations, where only energy *differences* count

But: Taken into account by gravity →Cosmological term ?

Cosmological constant : Possibly additional term in Einstein's field equations

May yield long range attraction/repulsion, according to sign

Invented by Einstein in order to guarantee static universes

Rejected by Einstein at the time of discovery of expansion of the Universe

Recently resurrected following the discovery of accelerated expansion

About the Higgs Field - VI

Zero point energy $= -\frac{1}{8} m_h^2 v^2 \sim \rho_{Higgs}$

Indeed: $\left[-\frac{1}{8} m_h^2 v^2 \right] = \underbrace{E^4}_{GeV^4} = E\left(E^{-1}\right)^{-3} \rightarrow \frac{E}{L^3}$ Energy density

$\rho_{Higgs} \sim 1.2 10^8 \;\; GeV^4$

By assuming ρ to be a cosmological term, compare:

$\rho_{observed} \sim 10^{-47} \;\; GeV^4$!

$\rightarrow \rho_{Higgs}$ 55 orders of magnitude too big

(and with the wrong sign...)

Quick fix: $V(v)$ can be set $= 0$ by adding a constant to $V(\phi)$

Constant apparently unrelated to m_h, v...

...to be chosen to an accuracy of 1 part out of 10^{55} !

Fine tuning problem, still essentially unsolved

Something missing?

About the Higgs Field - VII

Higgs boson: Quantum excitation of the field, mass m_H *not* given by the field

Further issue: $V(\phi)$ appearing in L: *Classical* potential

$\rightarrow$Must be quantized

$\rightarrow$Will be used perturbatively

$\rightarrow$Radiative corrections will modify the classical $V(\phi)$

Similar to vacuum polarization corrections to Coulomb potential in QED

(Uehling potential & Lamb shift)

Standard effect: Running constants, including λ

$$L_H = D_\mu \phi^\dagger D^\mu \phi - \mu^2 \phi^\dagger \phi - \lambda \left(\phi^\dagger \phi\right)^2$$

$$\lambda = \lambda\left(q^2\right)$$

$\rightarrow m_H$ modified by radiative corrections

Upon taking $\mu^2 < 0, \quad \lambda(0) > 0$

$\rightarrow \lambda$ evolution depending on $\beta - functions$

About the Higgs Field - VIII

Running couplings and β−functions:

$$\frac{dg^2}{d\ln Q^2} \equiv 4\pi\beta\left(g^2\right) = \underbrace{bg^4}_{1\text{ loop}} + \underbrace{O\left(g^6\right)}_{2\text{ loop}} + \cdots$$

$$\rightarrow \frac{dg_i^2}{d\ln Q^2} = 4\pi\beta_i\left(g_i^2\right) \simeq b_i g_i^4$$

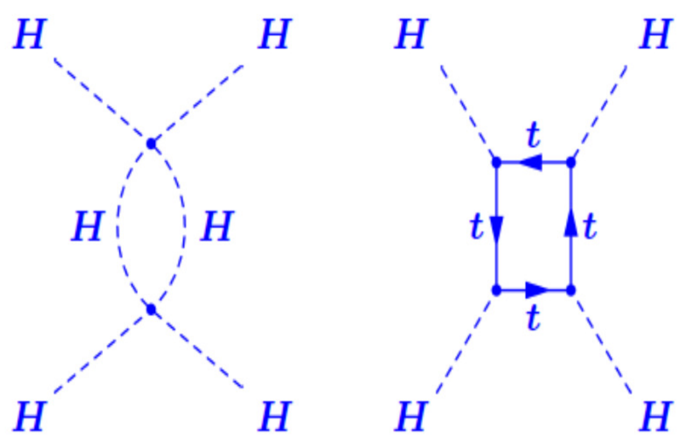
For the EW interaction:

$$b_g = -\frac{19}{6\cdot 16\pi^2}, \qquad b_{g'} = +\frac{41}{6\cdot 16\pi^2}$$

Higgs couplings:

$$\frac{d\lambda}{d\ln Q^2} = \frac{1}{32\pi^2}\left[24\left(\lambda^2 + h_t^2 - h_t^4\right) - 3\lambda\left(3g^2 + g'^2\right) + \frac{3}{8}\left(2g^4 + \left(g^2 + g'^2\right)^2\right)\right] \text{ Self}$$

$$\frac{dh_t}{d\ln Q^2} = \frac{1}{32\pi^2}\left[9h_t^3 - h_t\left(8g_s^2 + \frac{9}{4}g^2 + \frac{17}{12}g'^2\right)\right] \text{ Top (Yukawa)}$$



About the Higgs Field - IX

$$\frac{d\lambda}{d\ln Q^2} \sim \frac{3\lambda^2}{4\pi^2}$$ Neglect smaller contributions at large λ

$$\frac{d\lambda}{\lambda^2} \sim \frac{3}{4\pi^2} d\ln Q^2 \rightarrow -\frac{1}{\lambda(Q^2)} + \frac{1}{\lambda(\nu^2)} \sim \frac{3}{4\pi^2}\ln\frac{Q^2}{\nu^2}$$

$$\rightarrow \frac{1}{\lambda(Q^2)} \sim \frac{1}{\lambda(\nu^2)} - \frac{3}{4\pi^2}\ln\frac{Q^2}{\nu^2}$$

$$\lambda(\nu^2) = \frac{G_F m_H^2}{\sqrt{2}} \rightarrow \lambda(Q^2) \sim \frac{\lambda(\nu^2)}{1 - \frac{3}{4\pi^2}\lambda(\nu^2)\ln\frac{Q^2}{\nu^2}}$$

$\lambda \rightarrow \infty$ as $\frac{3}{4\pi^2}\lambda(\nu^2)\ln\frac{Q^2}{\nu^2} \rightarrow 1$ Diverging at 'Landau pole' $Q_{LP} = v\exp\left(\frac{2\pi^2}{3\lambda(\nu^2)}\right) = v\exp\left(\frac{2\sqrt{2}\pi^2}{3G_F m_H^2}\right)$

$\rightarrow$ New physics required at scale $\Lambda < Q_{LP} \rightarrow \ln\frac{\Lambda}{v} < \left(\frac{2\sqrt{2}\pi^2}{3G_F m_H^2}\right) \rightarrow m_H < \left(\frac{2\sqrt{2}\pi^2}{3G_F \ln\frac{\Lambda}{\nu}}\right)^{1/2} \sim \begin{matrix} O(140\ GeV),\ \Lambda \sim m_{Planck} \approx 1.2 10^{19}\ GeV \\ O(650\ GeV),\ \Lambda \sim 1\ TeV \end{matrix}$

About the Higgs Field - X

$$\frac{d\lambda}{d\ln Q^2} \sim -\frac{3h_t^4}{4\pi^2}$$ Neglect smaller contributions at small λ

$$\to d\lambda \sim -\frac{3h_t^4}{4\pi^2}\, d\ln Q^2$$

$$\to \lambda\left(Q^2\right) \sim \lambda\left(\nu^2\right) - \frac{3h_t^4}{4\pi^2}\ln\frac{Q^2}{\nu^2}$$

λ must stay $+ve$ in order to keep vacuum stable (!):

Don't like a too quick End of the World

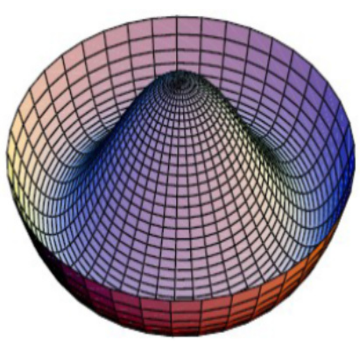
$$\to \lambda\left(\nu^2\right) > \frac{3h_t^4}{4\pi^2}\ln\frac{Q^2}{\nu^2} \to \frac{G_F m_H^2}{\sqrt{2}} > \frac{3h_t^4}{4\pi^2}\ln\frac{Q^2}{\nu^2} \text{ for some } Q \sim \Lambda$$

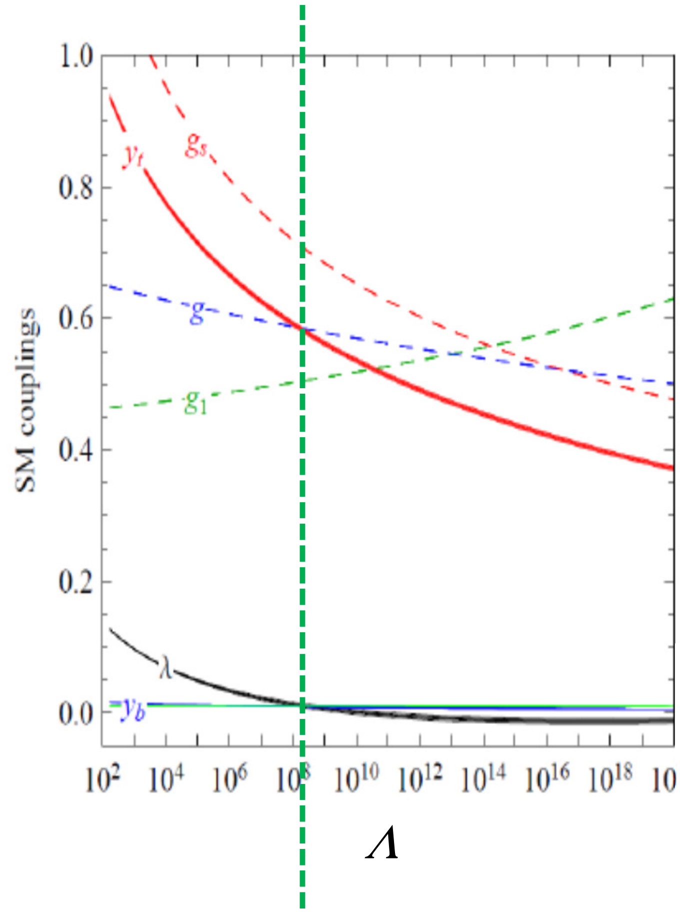
$$\to m_H > \left(\frac{3h_t^4}{\sqrt{2}\pi^2 G_F}\ln\frac{\Lambda}{\nu}\right)^{1/2}$$

About the Higgs Field - XI

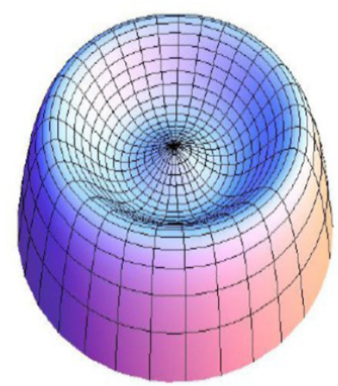
Running couplings:

Sombrero: $\lambda>0$
Relax





Dog Bowl: $\lambda<0$
End of the World
(sometime)

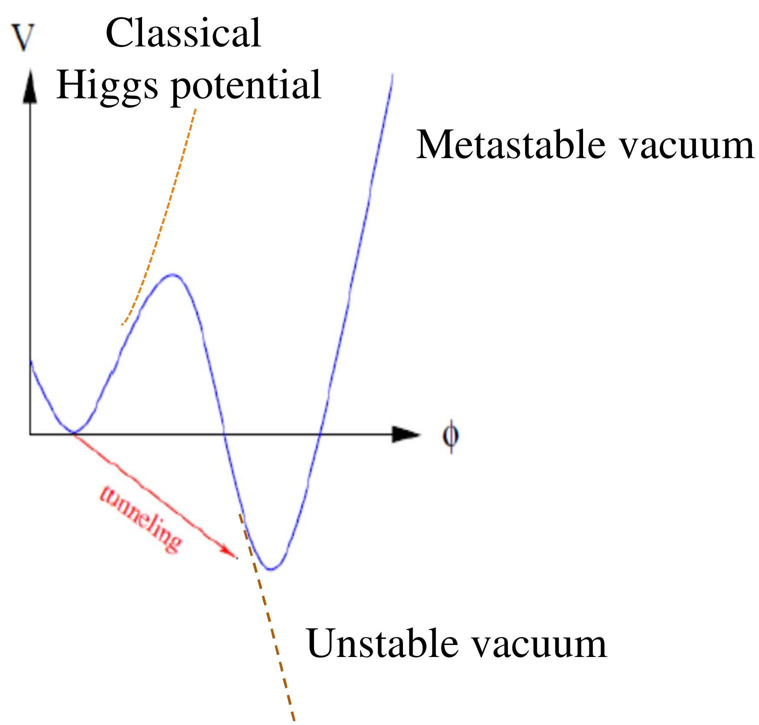


About the Higgs Field - XII

Radiative corrections leading to major changes in the effective Higgs potential at large ϕ values:

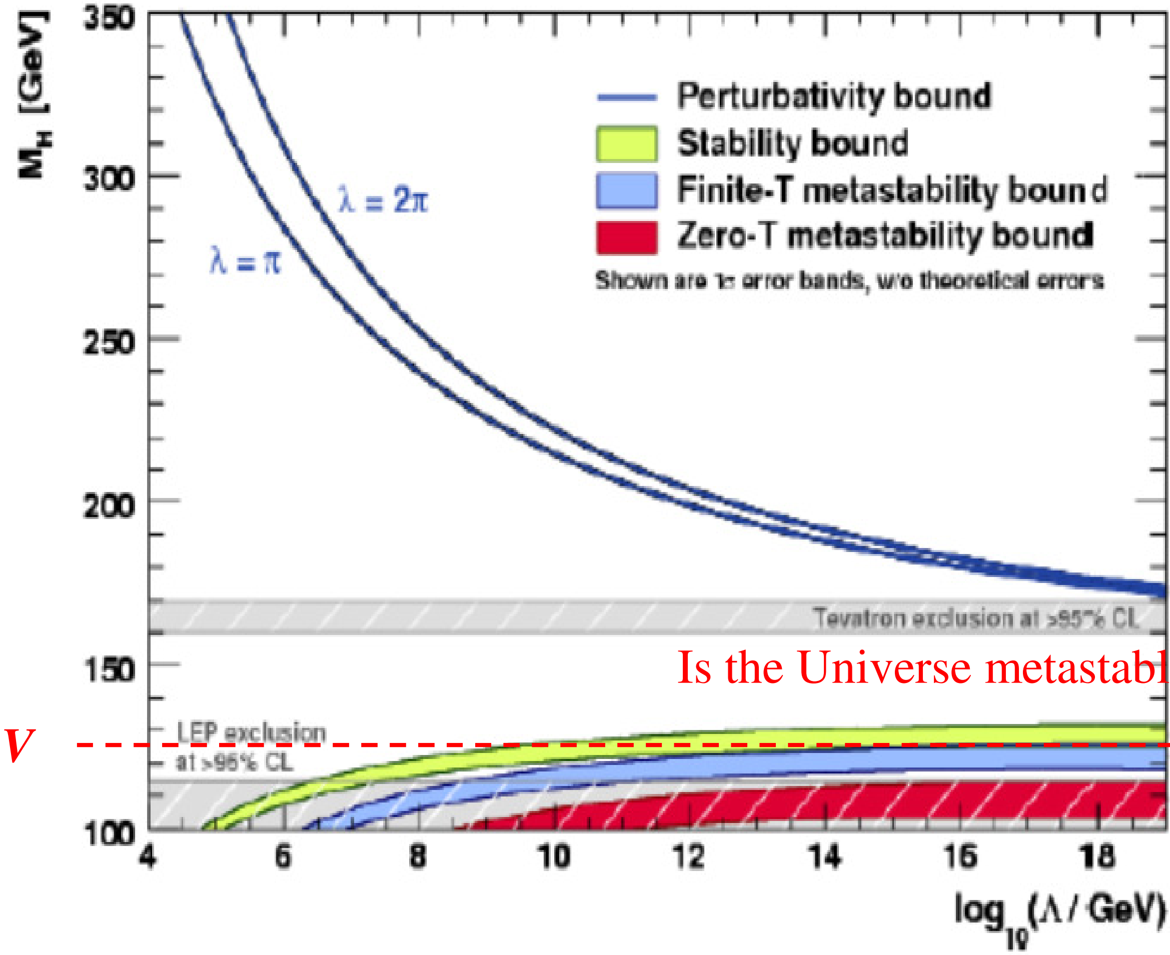
Details tied to m_H, m_t

Might induce vacuum instability/metastability through fast/slow tunneling



About the Higgs Field - XIII

Upper & lower bounds on m_H :

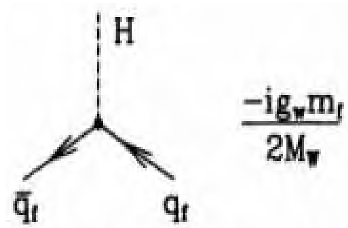


Is the Universe metastable??

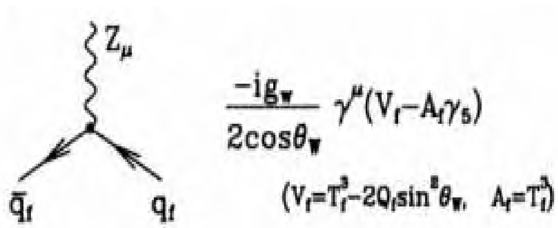
m_H = 126 GeV

Higgs Production - I

Start from H coupling to Fermions:



Compare to coupling to Z^0 :

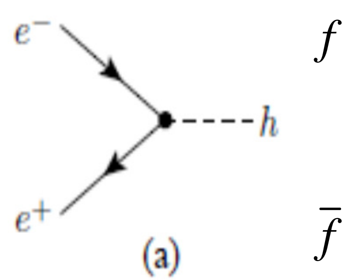


$\rightarrow H$ coupling down by a factor $\sim \frac{m_f}{m_W}$ as compared to Z^0

Higgs Production - II

First mode:

s-channel formation:



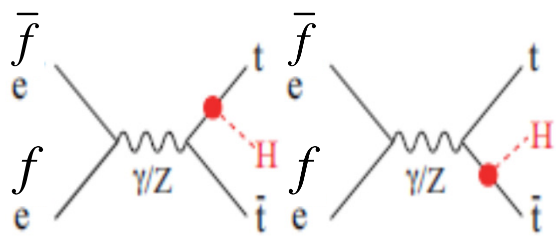
Ideal for lineshape scan, provided cross-section is big enough

Lepton colliders:

Tough requirements on luminosity, energy resolution

Higgs Production - III

Second mode:
H radiation from quarks, sizeable contribution from Top:



$t\bar{t}$ signature might be useful to tag

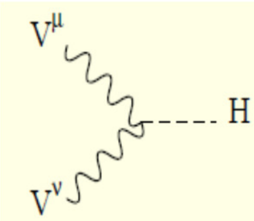
Higgs Production - IV

Shift to gauge bosons:

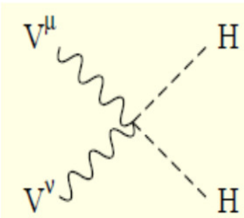
Exclude massless photon, gluon *at tree level*

[Photon, gluon *loop* contribution to be taken into account: See later]

More promising: W, Z mass very large



$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$

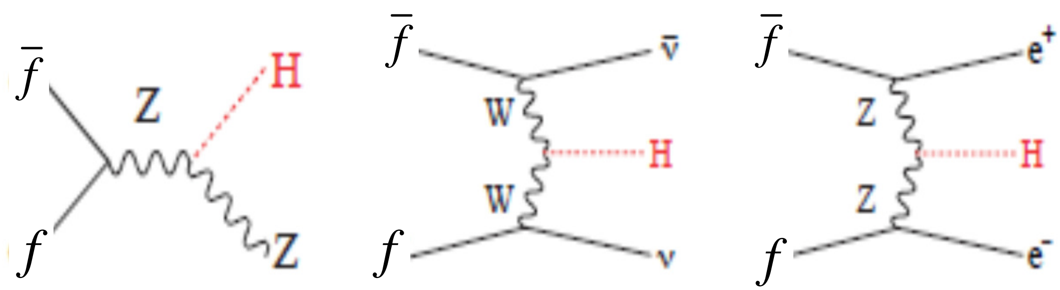


$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

Higgs Production - V

Best modes:

'Higgsstrahlung', 'Gauge boson fusion'

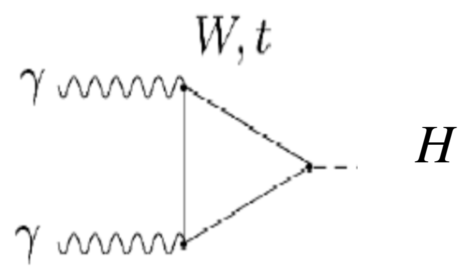


Higgs Production - VI

Beyond tree level: Very Important Loops

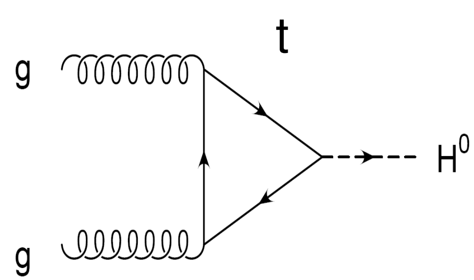
Lepton machines:

Interesting diagrams, also quite relevant to detection

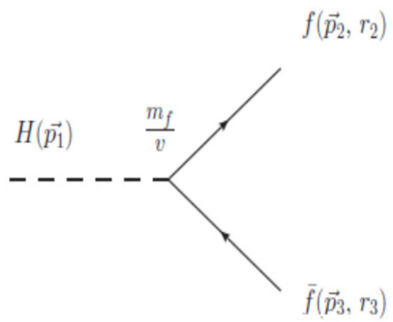


Parton machines:

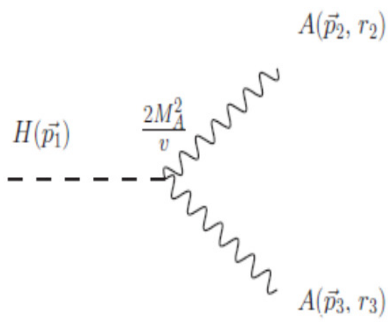
Dominant diagram at LHC



Higgs Decays - I



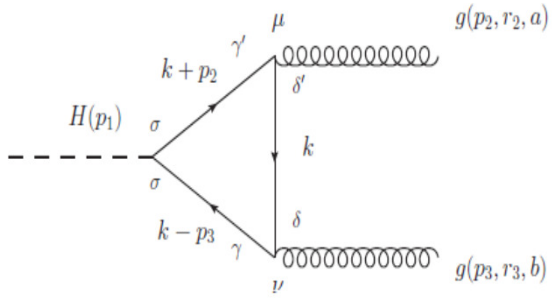
$$\Gamma(H \to f\bar{f}) = N_C \frac{1}{8\pi} \frac{m_f^2}{v^2} M_H \left(1 - \frac{4m_f^2}{M_H^2}\right)^{3/2}$$

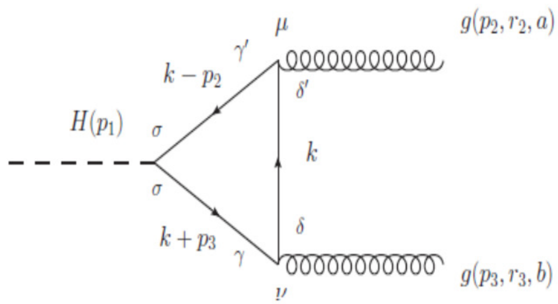


$$\Gamma(H \to WW) = \frac{1}{4\pi} \frac{M_W^4}{M_H v^2} \left(1 - \frac{4M_W^2}{M_H^2}\right)^{1/2} \left(3 + \frac{1}{4} \frac{M_H^4}{M_W^4} - \frac{M_H^2}{M_W^2}\right)$$

$$\Gamma(H \to ZZ) = \frac{1}{8\pi} \frac{M_Z^4}{M_H v^2} \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{1/2} \left(3 + \frac{1}{4} \frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right)$$

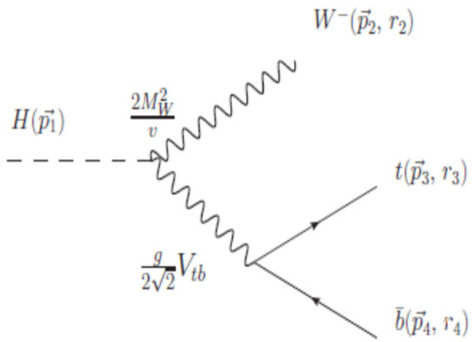
Higgs Decays - II





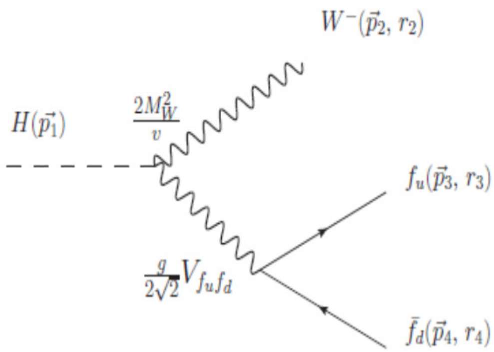
$$\Gamma(H \to gg) = \frac{M_H^3}{8\pi\, v^2}\left(\frac{\alpha_s}{\pi}\right)^2 n^2\, |D(n)|^2$$

Higgs Decays - III



$$\Gamma(H \to W t b) = N_C \frac{g^2}{2v^2} \frac{M_W^4}{M_H} |V_{tb}|^2 \int dQ_3 \frac{G^{\beta\nu} T_{\beta\nu}}{[s_{34} - M_W^2]^2}$$

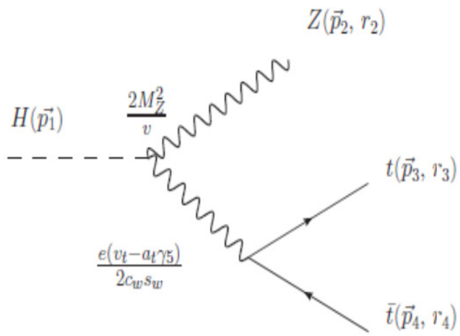
3-body phase space factor



$$\Gamma(H \to W f_u f_d) = \frac{g^2}{v^2} \frac{3M_W^2}{256\pi^3} M_H S(x)$$

3-body phase space factor

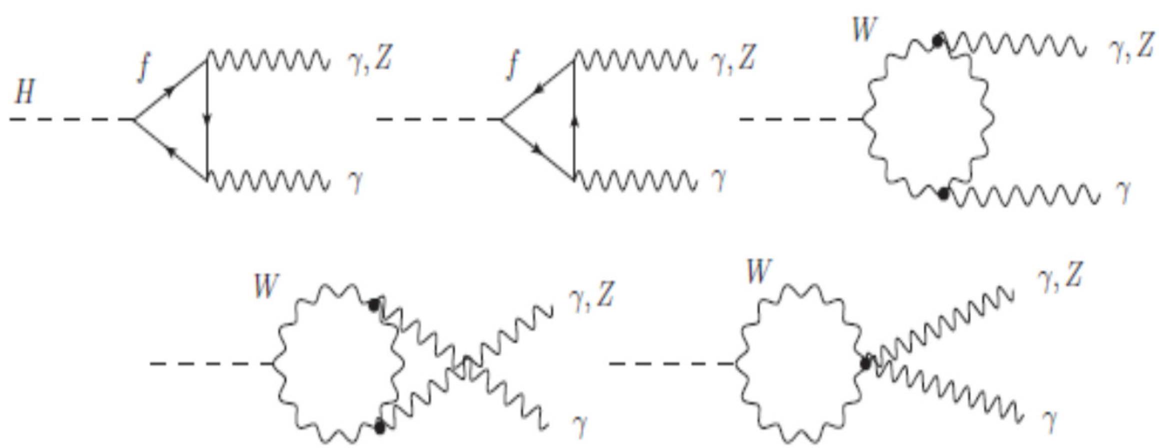
Higgs Decays - IV



$$\Gamma(H \to Z f \bar{f}) = \frac{g^2}{v^2} \frac{3M_Z^2}{256\,\pi^3} M_H\, S(x) \frac{R(\theta_w)}{\cos^2\theta_w} \left(\frac{7}{12} - \frac{10}{9}\sin^2\theta_w + \frac{40}{27}\sin^4\theta_w\right)$$

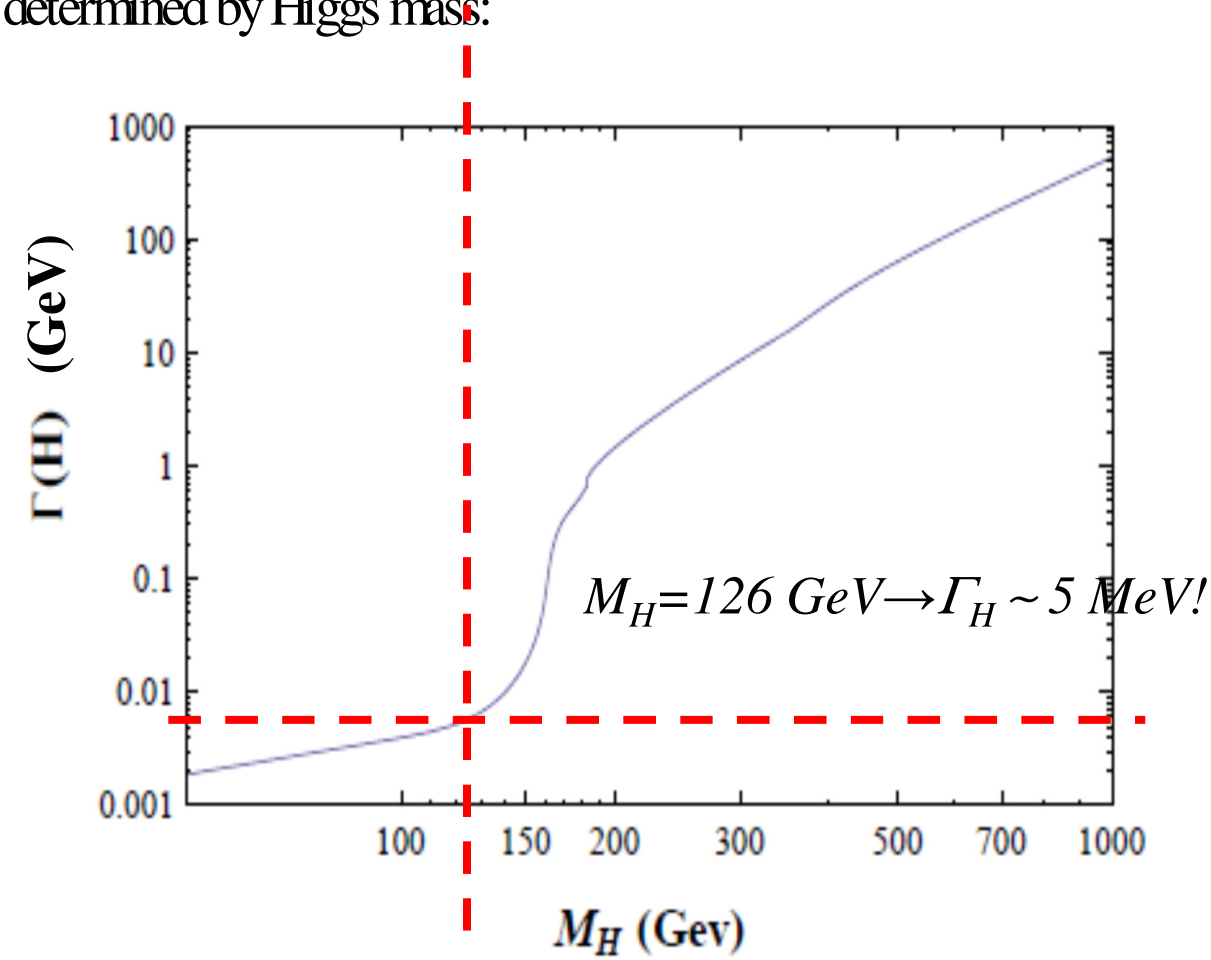
3-body phase space factor

$$\Gamma(H \to Z/\gamma, \gamma)$$



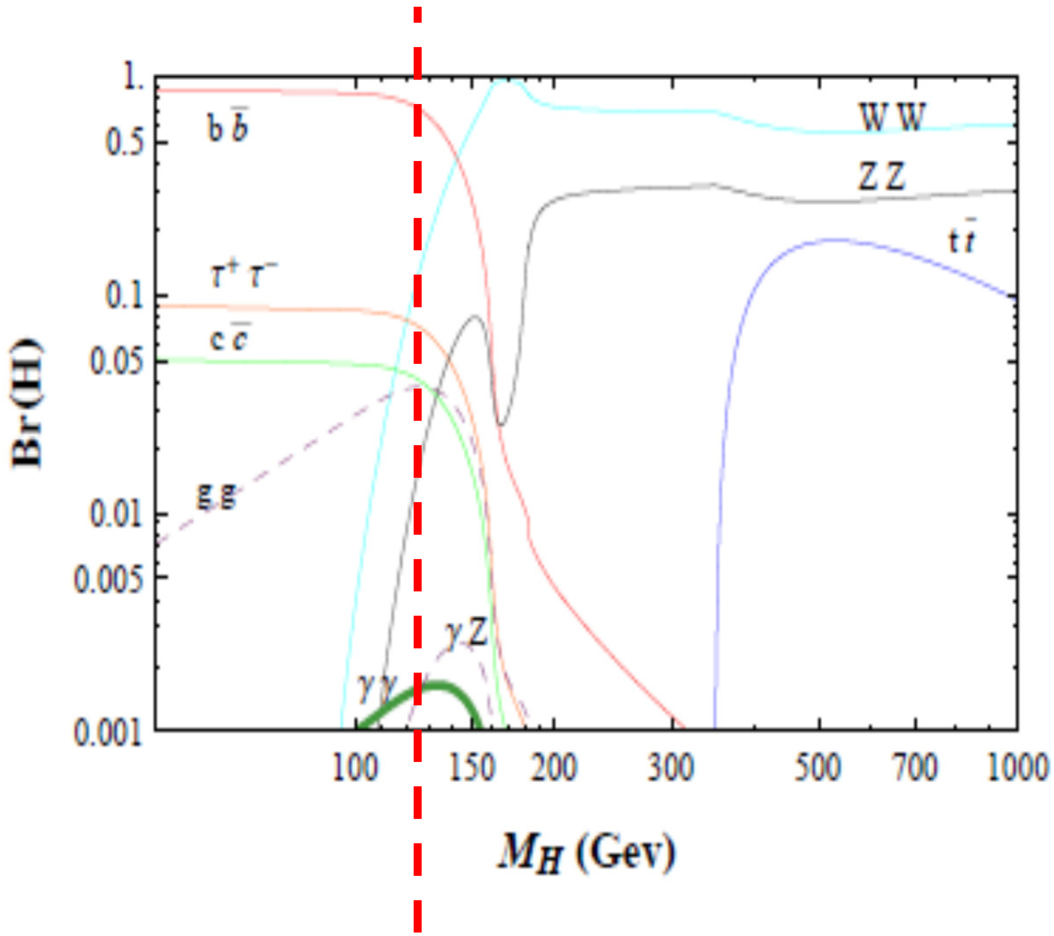
Higgs Decays - V

H decays entirely determined by Higgs mass:

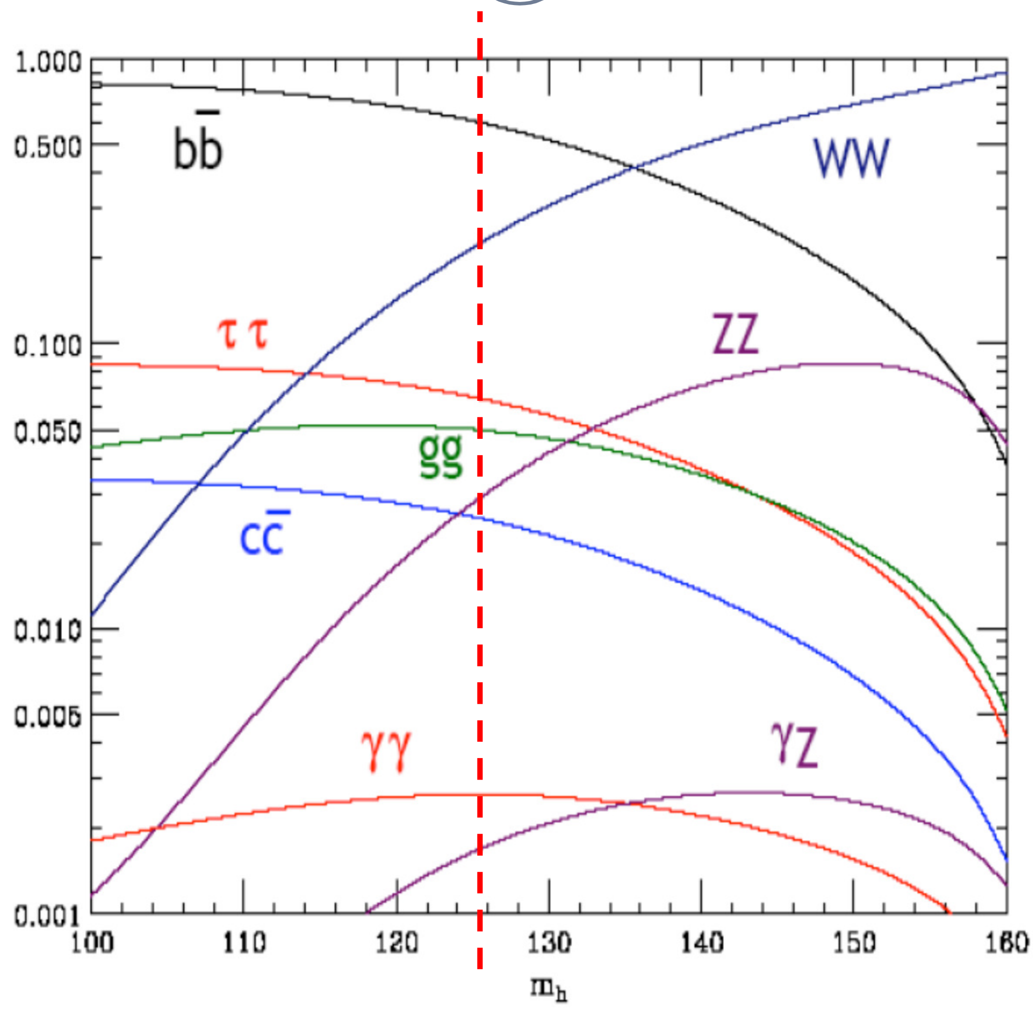


Higgs Decays - VI

H branching ratios:

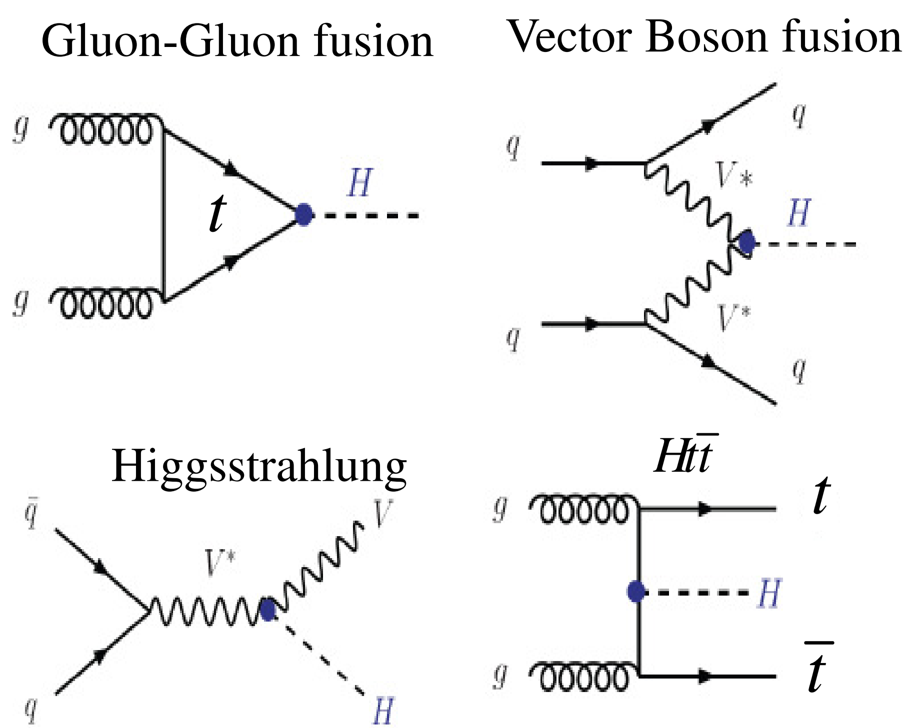


Higgs Decays - VII



Parton Collider - I

Dominant diagrams for H production:



Parton Collider - II

Basic ingredient: PDFs

Quarks: Look for heavy ones

Tree diagrams: Best bet is with b

Factor $\frac{m_b^2}{M_W^2} \sim 3\ 10^{-3}$ encouraging

But: No b-quark beams, must rely on $b\bar{b}$ sea inside the nucleon

b-quark partonic density small...

Taking H production at small rapidity $y \sim 0$, with a 7 TeV beam $x \sim 10^{-2}$

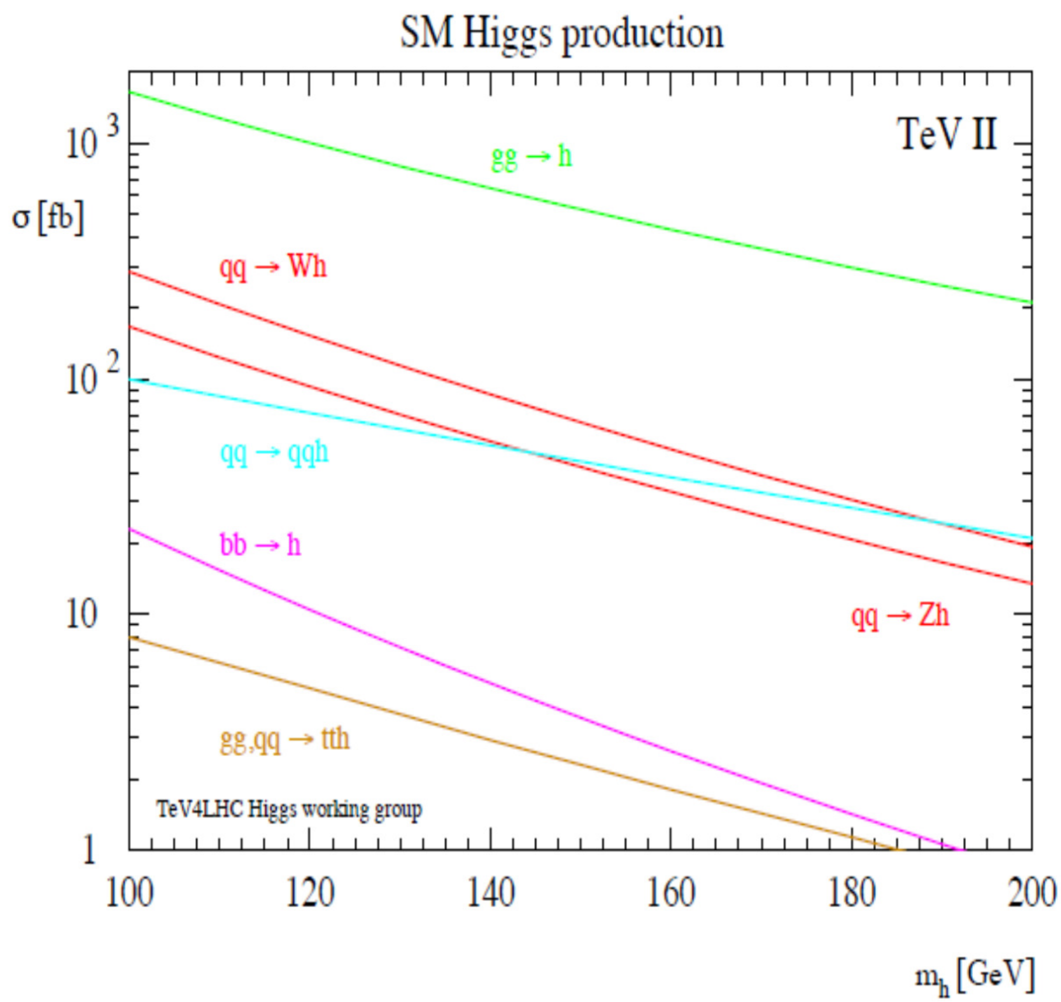
$\rightarrow$Incident flux of sea b-quarks very small

Gluons: Main contribution

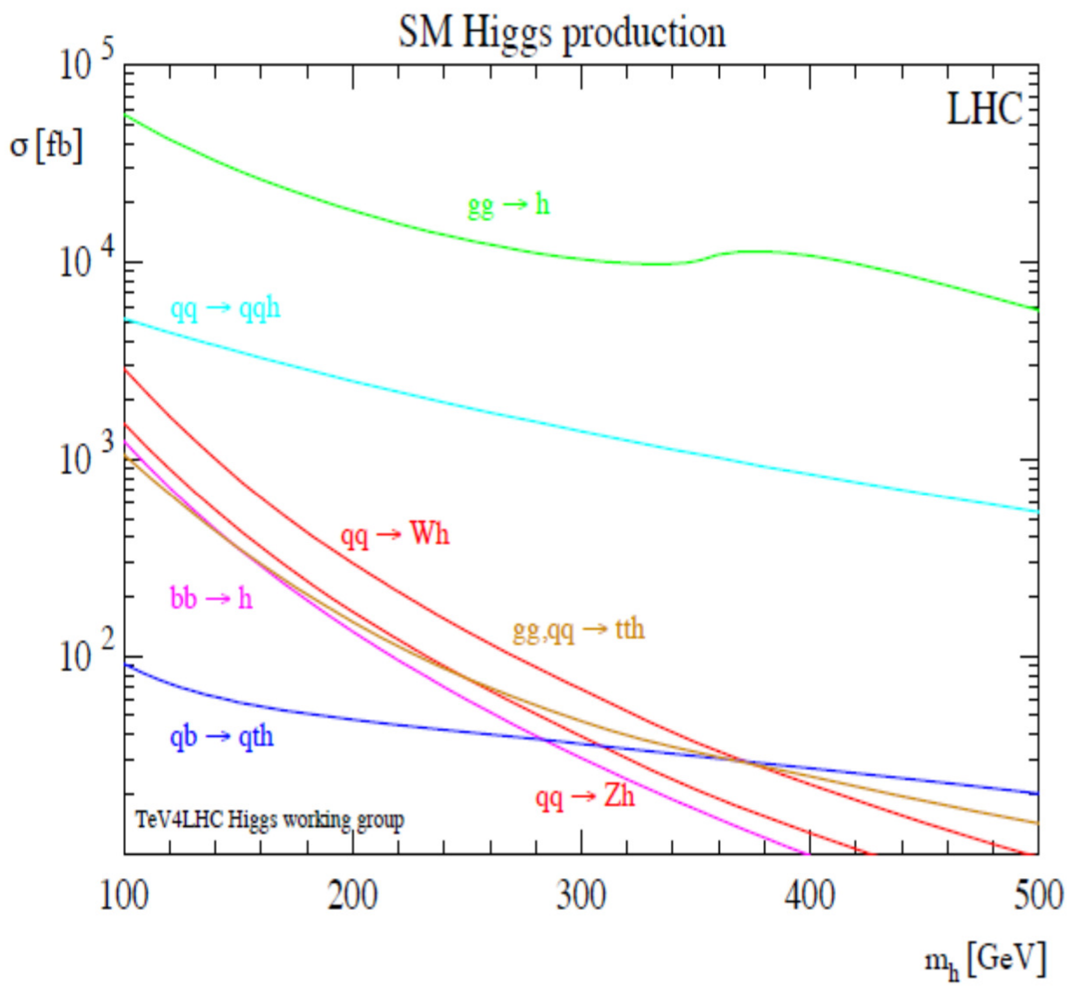
Loop diagrams, dominated by t quark

PDF somewhat dependent on Q^2

Parton Collider- III

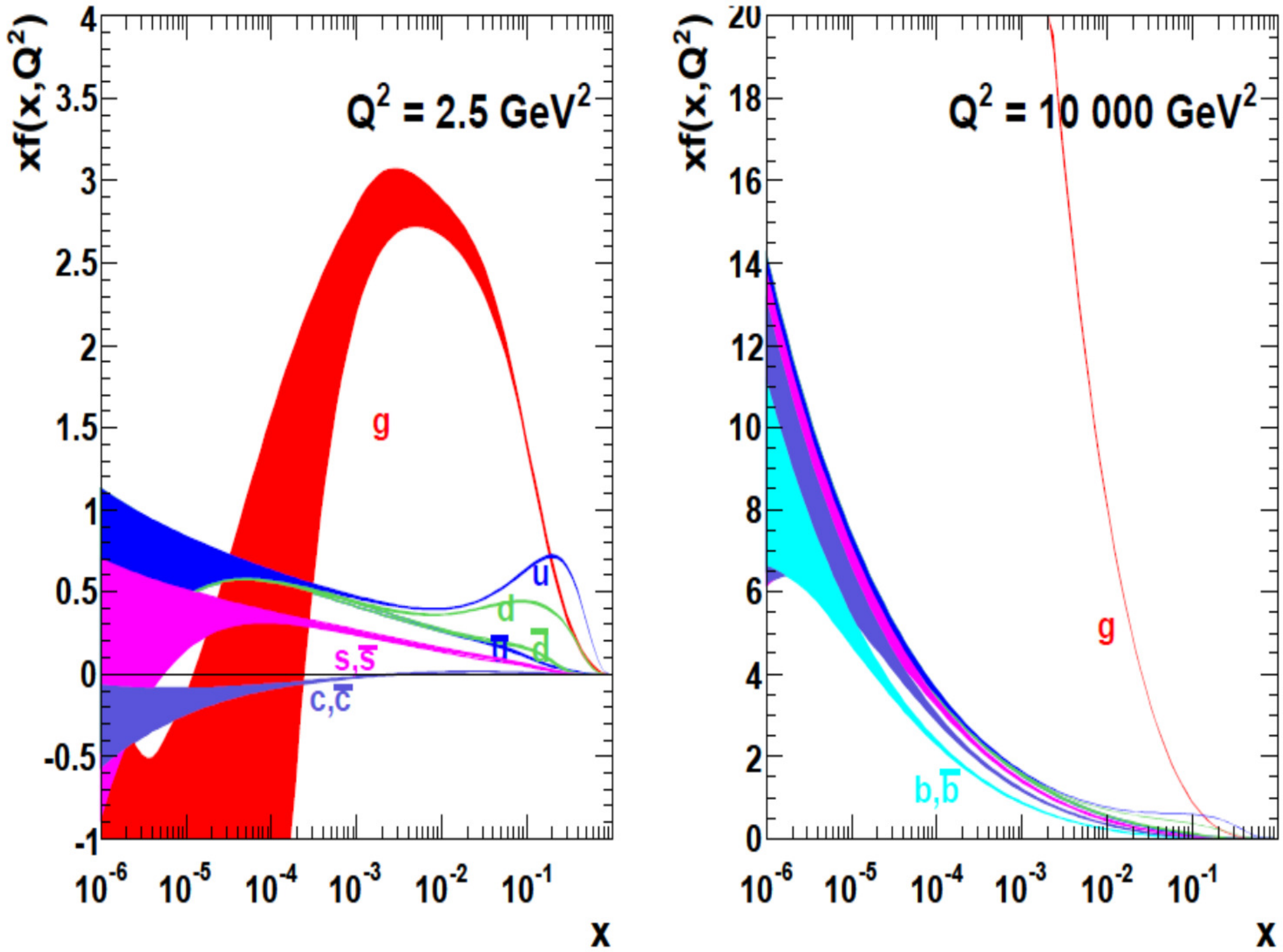


Parton Collider- IV

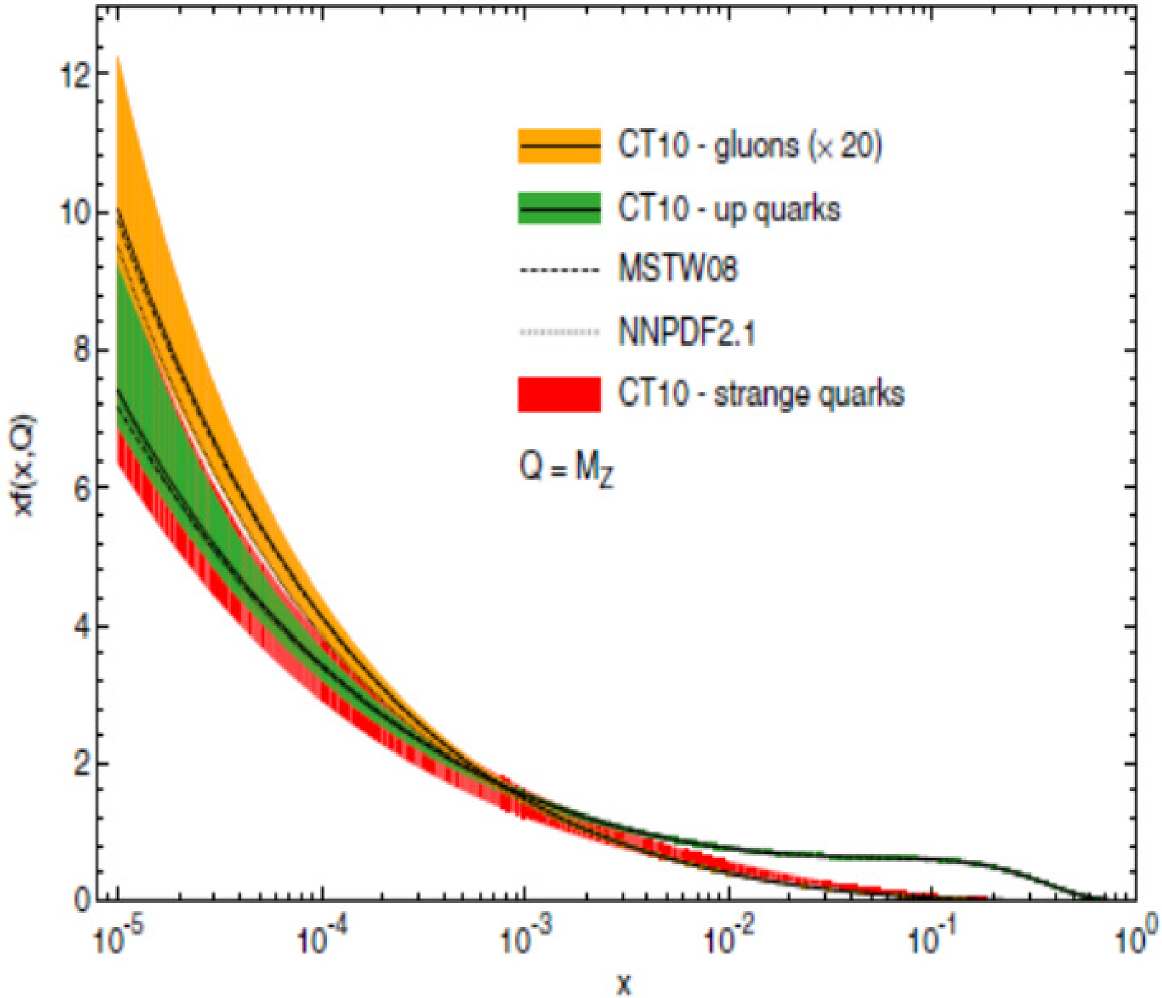


Parton Collider - V

Parton densities:

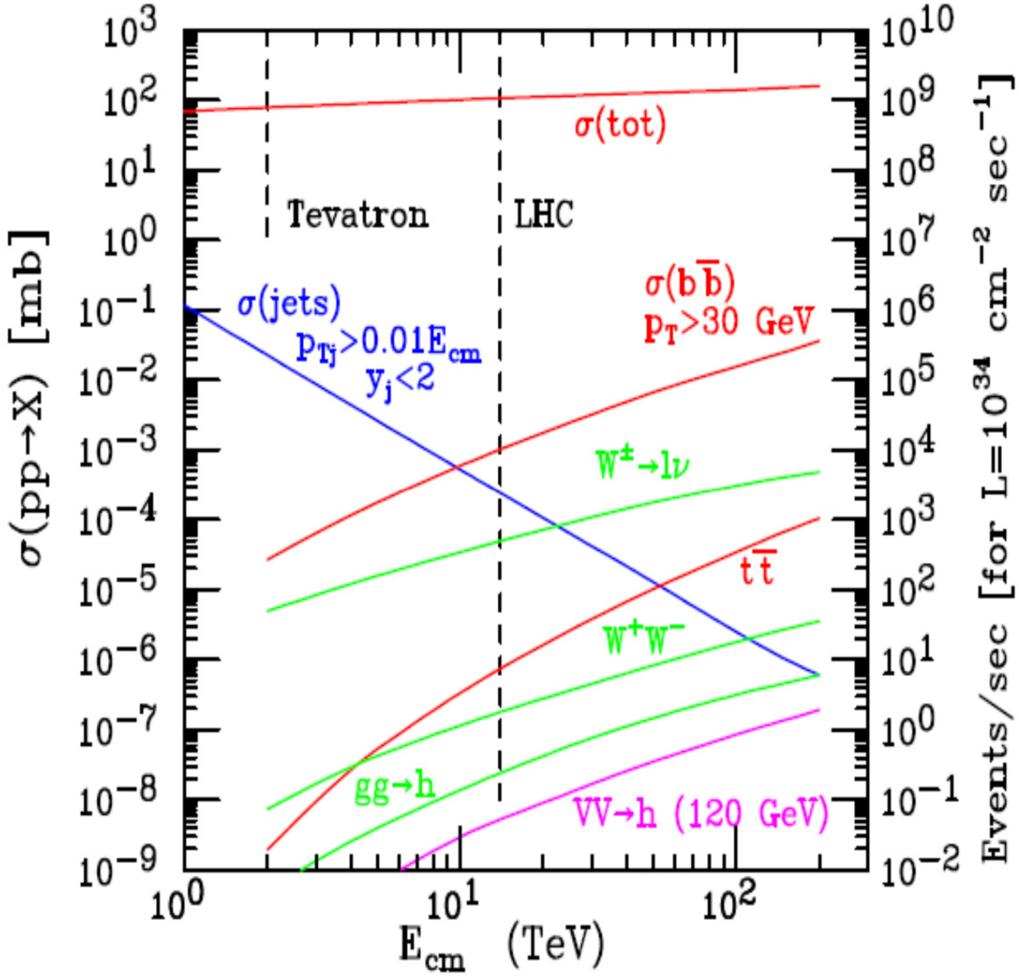


Parton Collider - VI



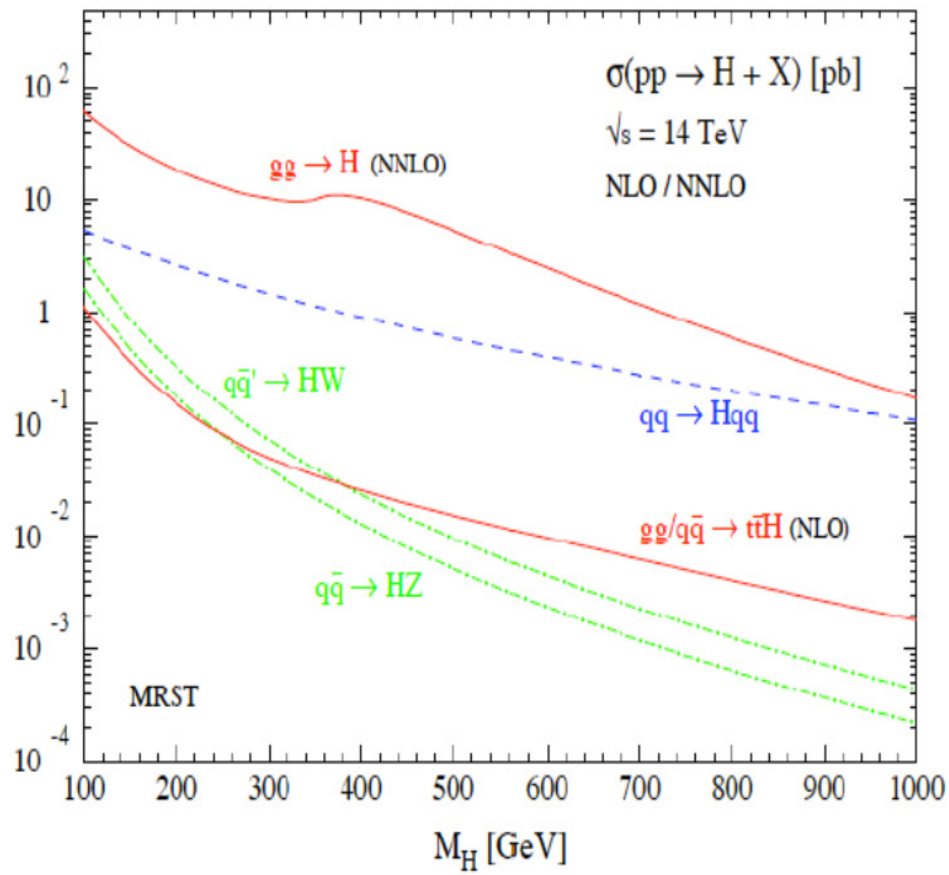
Parton Collider - VII

Expected cross sections for parton colliders:



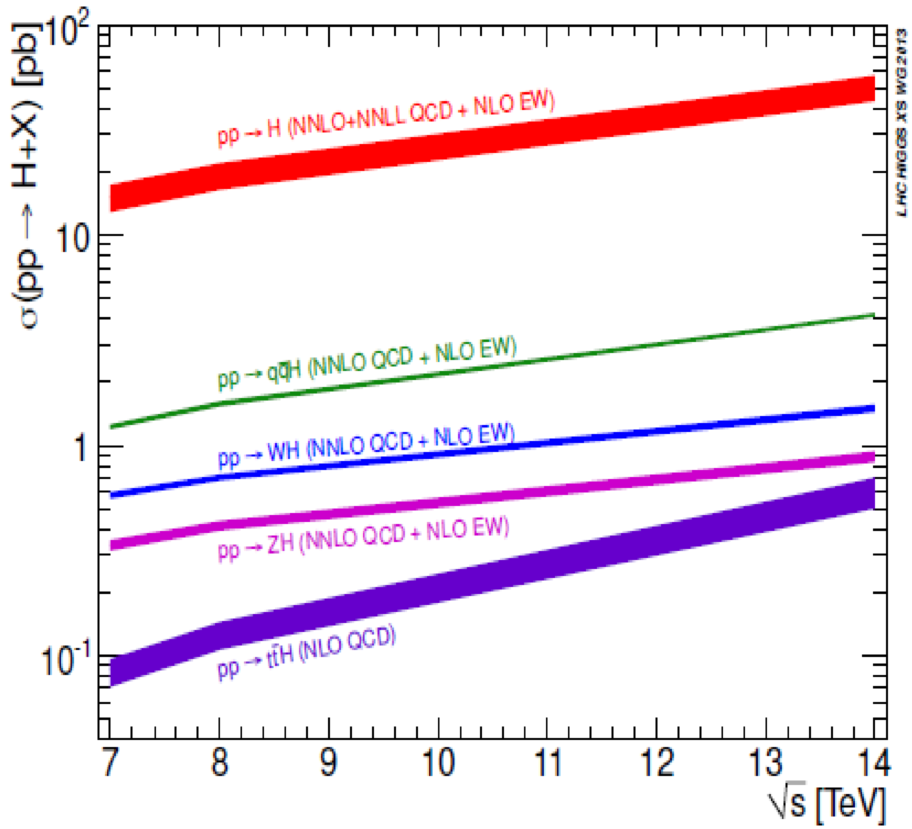
Parton Collider - VIII

Results for LHC cross sections

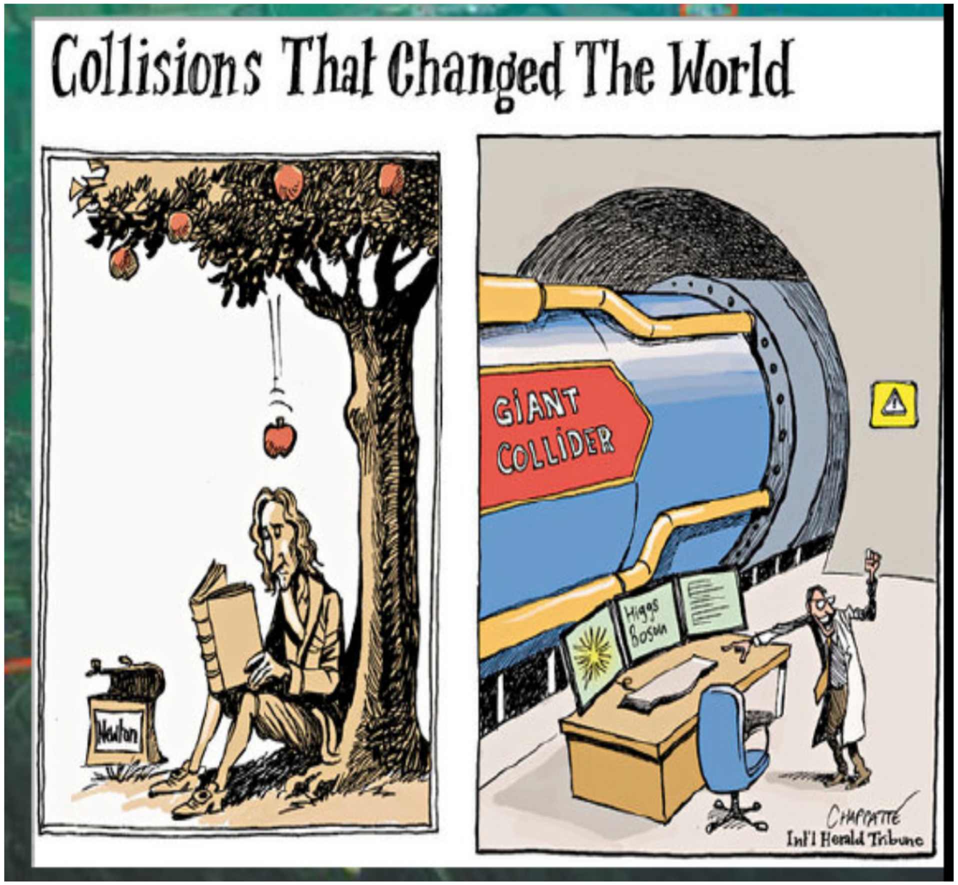


Parton Collider - IX

Cross-sections for a 126 GeV Higgs



LHC: Machine - I



LHC: Machine - II

LHC dipole field 8.3 T

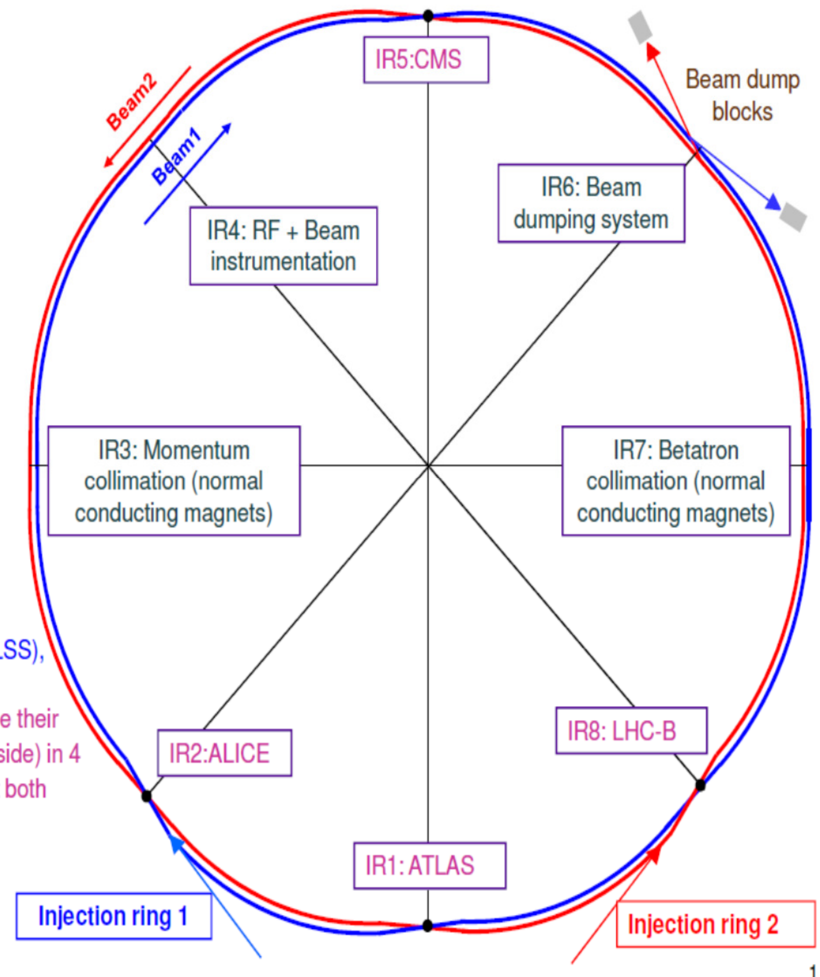
(HERA/Tevatron ~4 T)

LHC pp ~ 10^{34} $cm^{-2}\ s^{-1}$

(Tevatron pp $3x10^{32}$ $cm^{-2}\ s^{-1}$) (SppbarS pp $6x10^{30}$ $cm^{-2}\ s^{-1}$)

LHC Layout

- 8 arcs.
- 8 straight sections (LSS), ~ 700 m long.
- The beams exchange their positions (inside/outside) in 4 points to ensure that both rings have the same circumference !



LHC: Machine - III

$R = L\sigma$ Rate, Luminosity, Cross-Section

$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}$$

k = number of bunches = 2808

N = no. protons per bunch = 1.15×10^{11}

f = revolution frequency = 11.25 kHz

σ^*_x, σ^*_y = beam sizes at collision point (hor./vert.) = 16 mm

High L:

Many bunches (k)

Many protons per bunch (N)

A small beam size $\sigma^*_u = (\beta^*\varepsilon)^{1/2}$

β^* : Beam envelope (optics)

ε : Phase space volume occupied by the beam (constant along the ring)

High beam "brilliance" N/ε (particles per phase space volume)
→ Injector chain performance

Small envelope
→ Strong focusing

Optics property

Beam property

LHC: Machine - IV

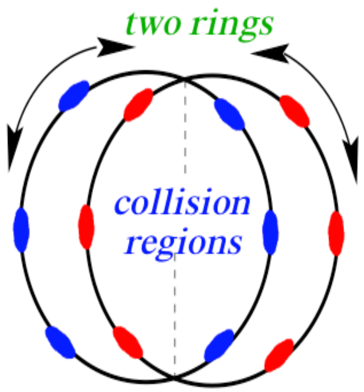
$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

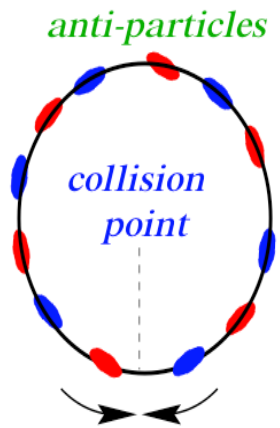
LHC: ρ = 2.8 km given by LEP tunnel

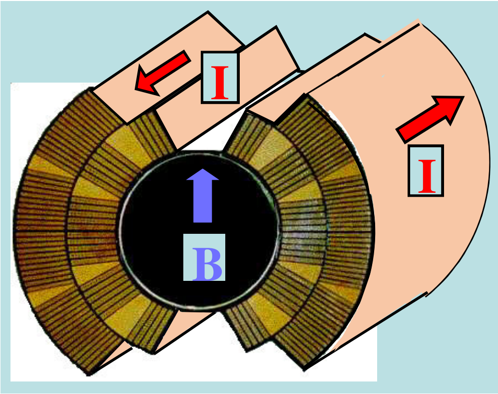
To reach p = 7 TeV/c given a bending radius of ρ = 2805 m:

Bending field : B = 8.33 T

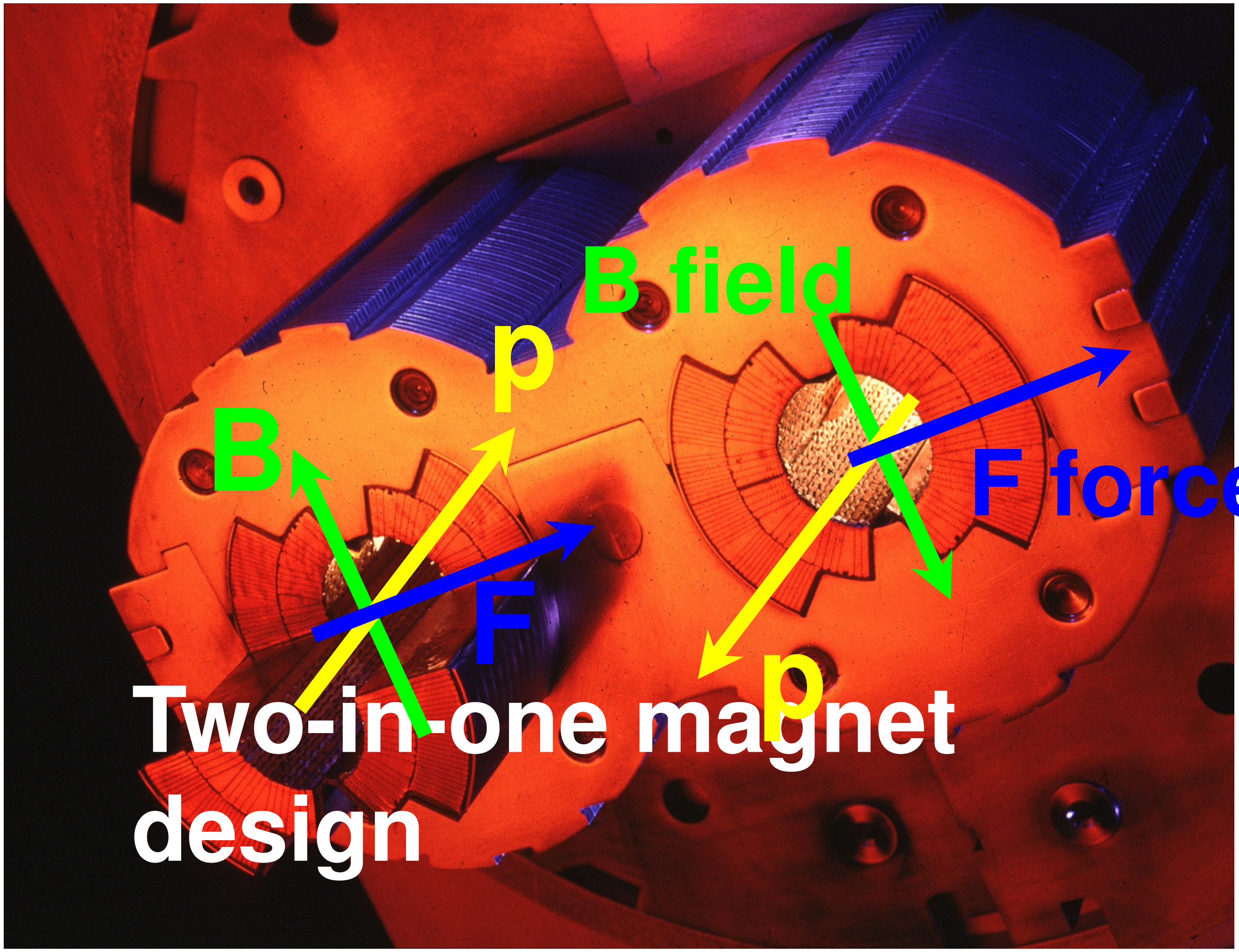
→Superconducting magnets





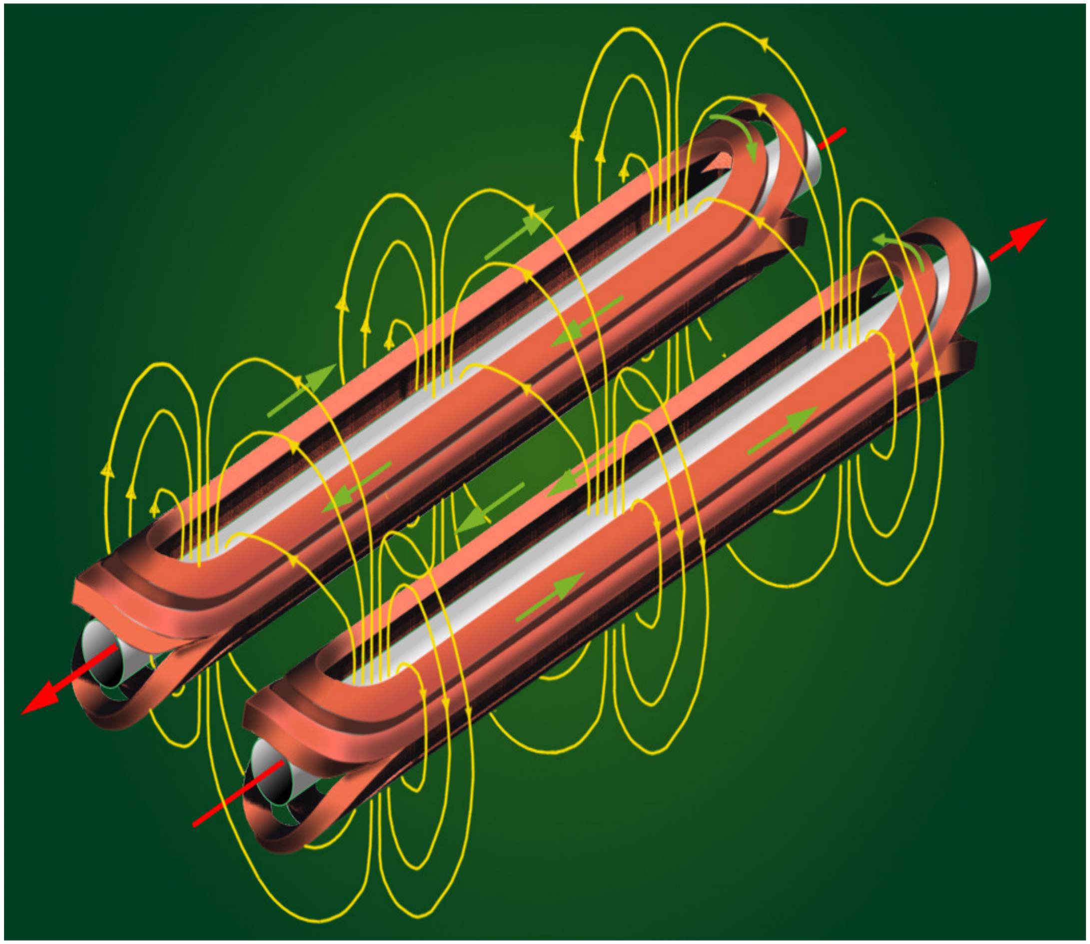


LHC: Machine - V



LHC: Machine - VI

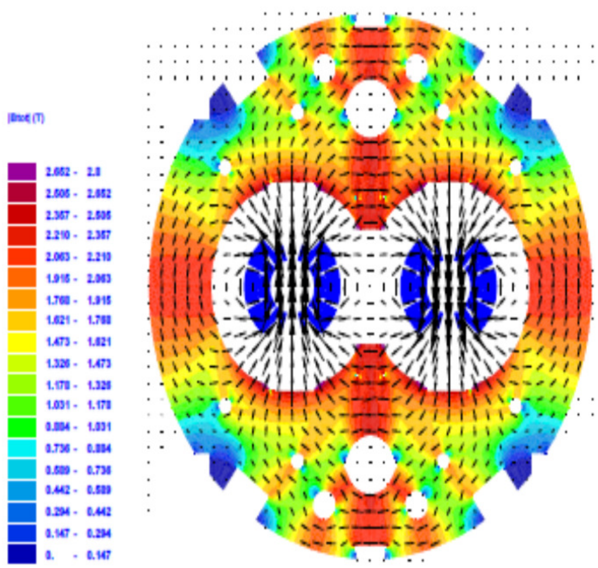
Superconducting coils:

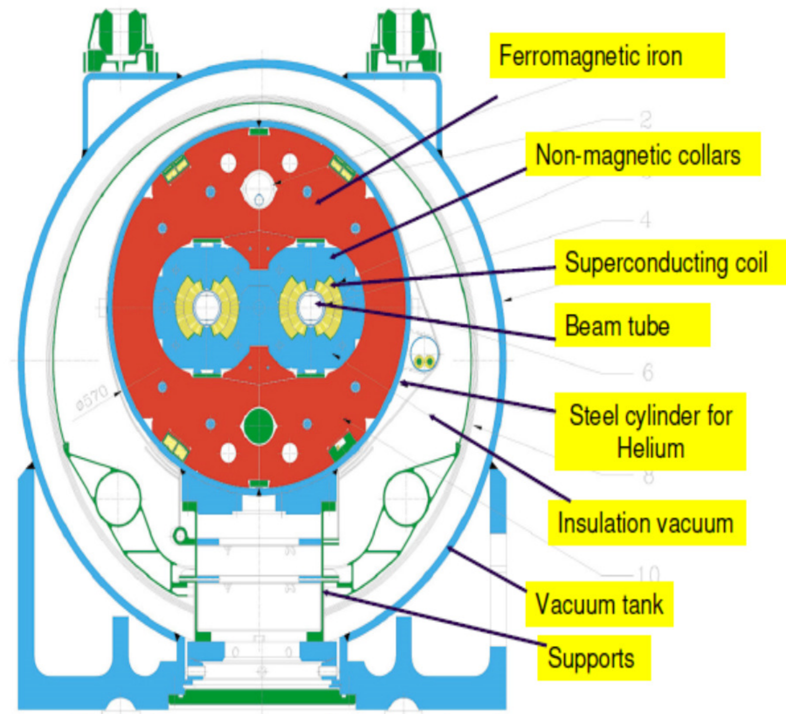


LHC: Machine - VII

LHC main dipole:

Two magnets in a single module





Weight (magnet + cryostat) ~ 30 tons, length 15 m

LHC: Machine - VIII

RF system:

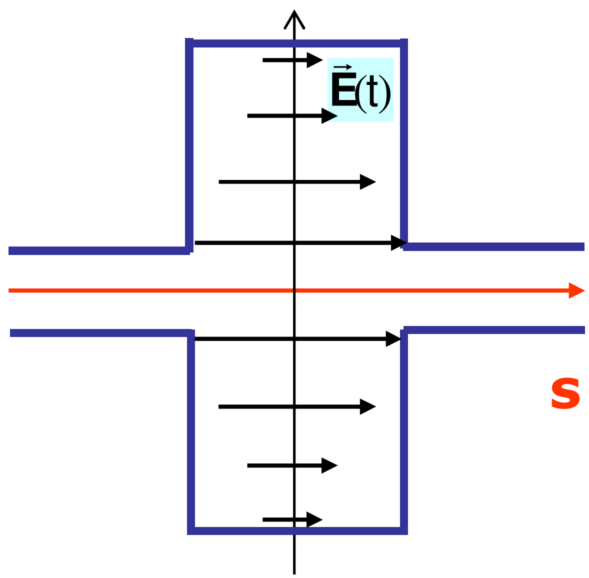
4 + 4 Superconducting RF cavities

400 MHz

$\sim$0.5 MeV/turn

20' for 450 GeV $\rightarrow$ 7 TeV

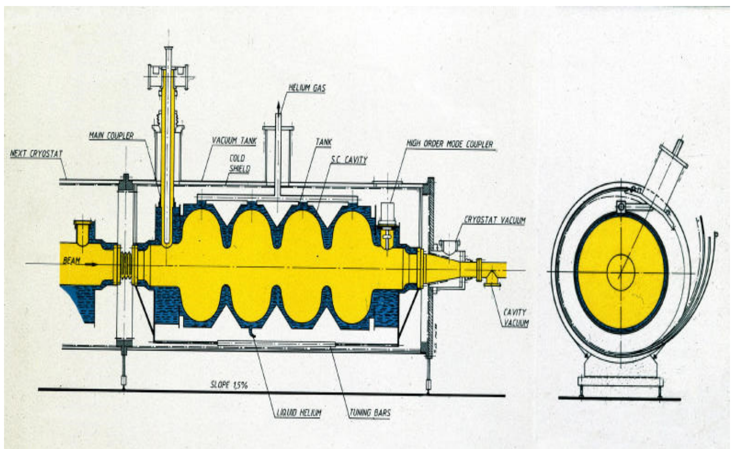
Synchrotron radiation loss



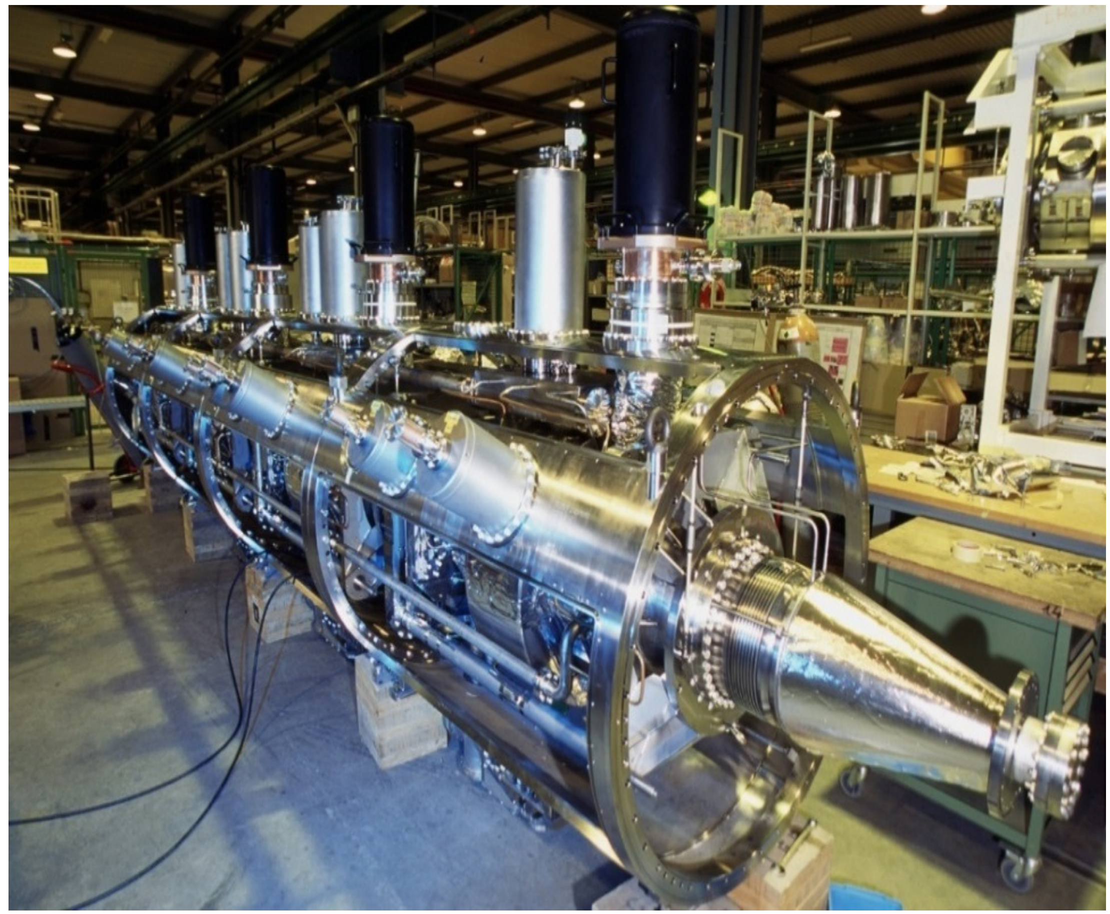
LHC @ 3.5 TeV	0.42 keV/turn
LHC @ 7 TeV	6.7 keV /turn
LEP @ 104 GeV	~3 GeV /turn

LHC: Machine - IX

Superconducting cavity



SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT



H - I

Selecting best decay channels for detection:

Strongly dependent on (unknown) M_H

By taking $M_H < 2M_W$

$b\bar{b}$: Large $BR > 50\ \%$, good signature (secondary vertexes), *lots* of QCD background

$\tau^+\tau^-$: Large $BR \sim 7\ \%$, somewhat harder than $b\bar{b}$ (neutrinos)

$\gamma\gamma$: Tiny $BR \sim 2\ 10^{-3}$, small background, experimentally challenging

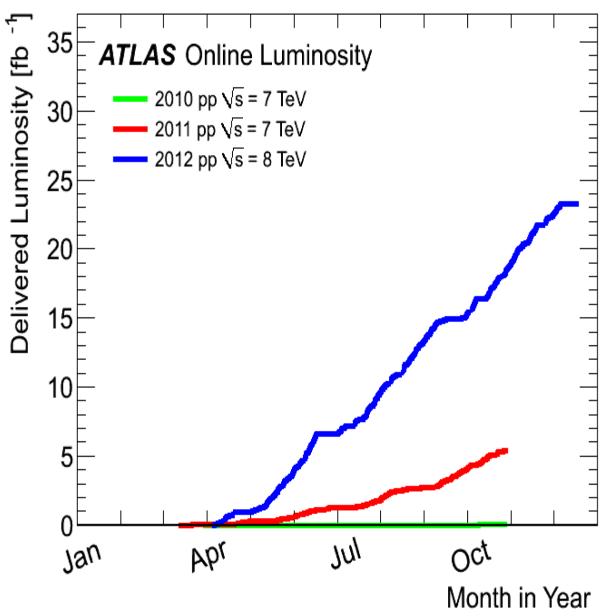
gg : Large $BR \sim 5\ \%$, 2 jets, *lots* of QCD background

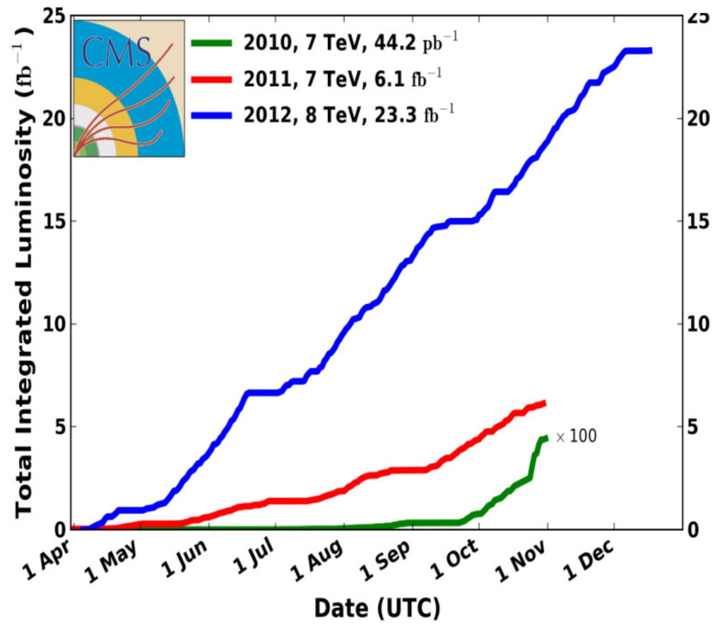
ZZ^*: Small $BR \sim 3\ \%$, small background in the 4 leptons mode

WW^* : Large $BR \sim 20\ \%$, sizeable QCD background in the 4 jets mode, harder than ZZ^* in leptonic modes (neutrinos)

H - II

Total integrated luminosity: $\sim 30\, fb^{-1}$ / experiment



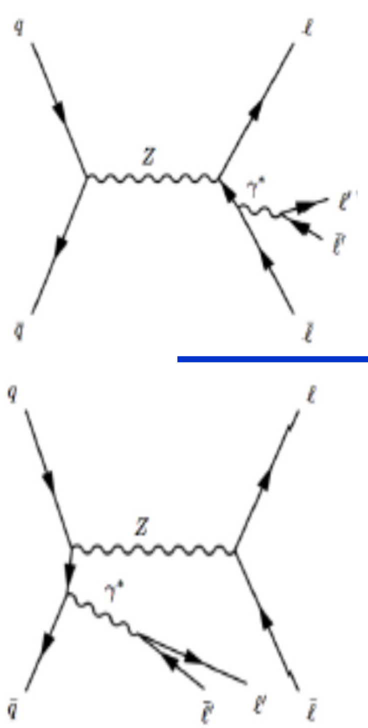


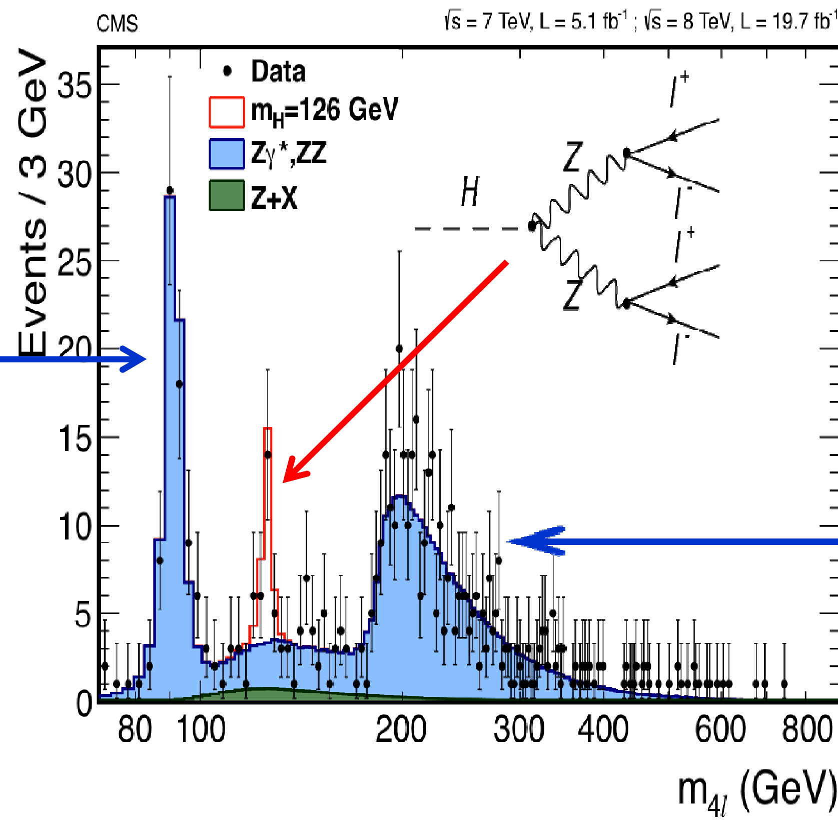
Phenomenal performance:

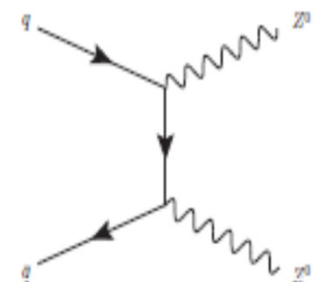
- Record luminosity (> 5 x 10^{33}) obtained soon after startup in 2012
- Sustained data collection rate of > 1.0 fb^{-1} /wk
- Delivered/recorded @ 8 TeV = [23.3 / 21.3 (ATLAS) , 21.8 (CMS)] fb^{-1}

H - III

4 leptons: ~7σ observation

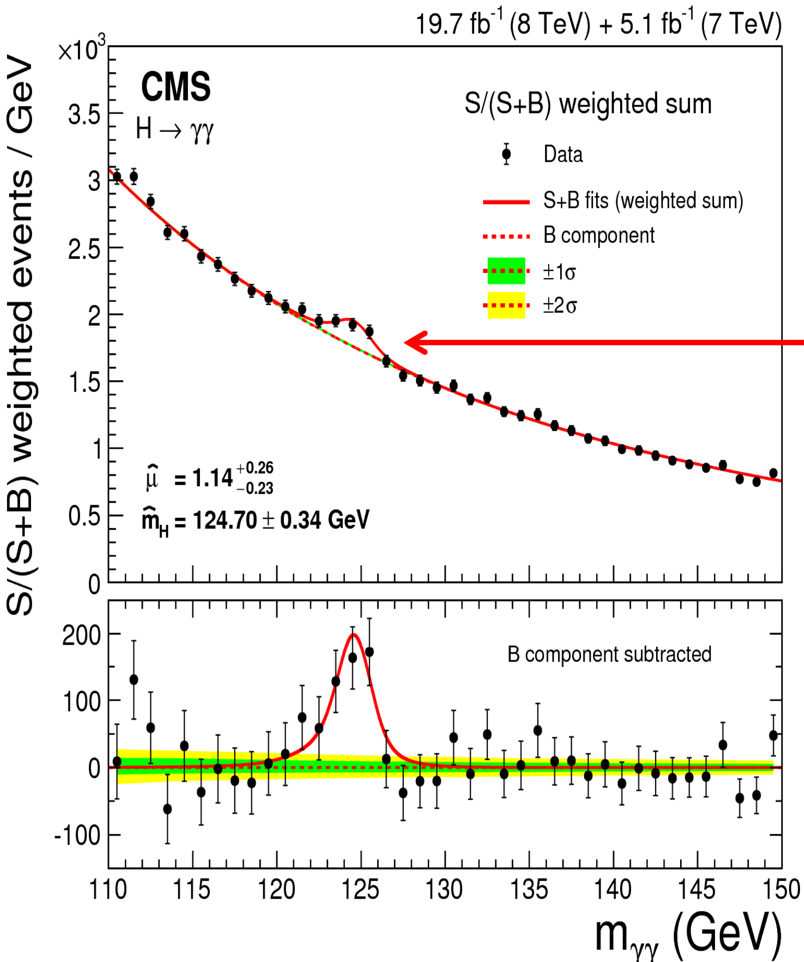


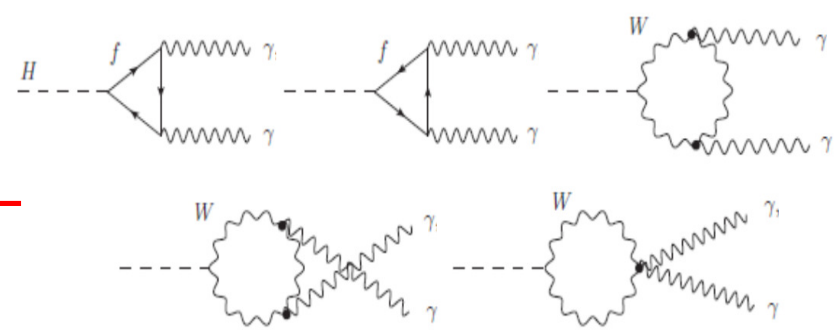




H - IV

2 γ's: ~6 σ observation





H - V

Signal strength:

	ATLAS (expected)	ATLAS (observed)	CMS (expected)	CMS (observed)
$h \to \gamma\gamma$	4.1	7.4	5.2	5.7
$h \to ZZ$	4.4	6.6	6.7	6.8
$h \to WW$	3.7	3.8	5.8	4.3
$h \to \tau\tau$	3.2	4.1	3.6	3.4
$h \to bb$	1.6	~0	2.1	2.1

H - VI

Combined mass: All modes

$$m_H\left(\text{ATLAS}\right) = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})$$

$$m_H(\text{CMS}) = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$$

Many more results on spin/parity, couplings, width...

....Next time!